U.S. DEPARTMENT OF ENERGY

OFFICE OF SCIENCE

Closeout Report on the DOE/SC CD-3 Review of the

Muon to Electron Conversion Experiment (Mu2e) Project

Fermi National Accelerator Laboratory

June 14-16, 2016

Kurt Fisher

Committee Chair

Office of Science, U.S. Department of Energy

http://www.science.doe.gov/opa/

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SC2
Superconducting Solenoids

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LEGEND

SC Subcommittee
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COUNT: 23 (excluding observers)

Charge Questions

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review?

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work?

3. Are the current project cost and schedule projections consistent with the baseline cost and schedule in the Project Execution Plan (PEP). Is the contingency adequate for the risks?

4. Are the management and resources adequate to deliver the proposed technical scope within the baseline budget and schedule as specified in the PEP?

5. Are the ES&H aspects being properly addressed, given the project's current stage of development?

6. Is the documentation required by DOE Order 413.3B for CD-3 complete?

7. Are there any outstanding issues that need to be addressed?

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review? Yes, The Accelerator KPP was modified as recommended and the Project Execution Plan was updated; and every Accelerator subsystem has been vetted by an independent final design review with many subsequent recommendations which the project has utilized.

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work? Yes, Overall Mu2e Accelerator Upgrade designs are 87% complete.

6. Is the documentation required by DOE Order 413.3B for CD-3 complete? Yes, some documents still need sign-off

7. Are there any outstanding issues that need to be addressed? No

Findings:

- All Accelerator Upgrades L3 subprojects have undergone independent final design reviews and a Director's review since the last DOE review.
  - All of these reviews indicated a CD-3 level of design maturity and readiness to begin the implementation phase of the schedule.
  - All recommendations from these reviews have been tracked and responses documented. Action is complete on 40 of the 43 recommendations received.
- The Mu2e Accelerator Upgrades approved PEP BAC = $39.799 M
  - Present BAC = $41.014 M (DBAC = $1.215 M = 3% × BAC)
  - The March 2016 EAC is $1.206 M above BAC which is within the estimate uncertainty of the baseline budget
- Accelerator cost and schedule performance since baselining in April 2015 has been satisfactory. Overall CPI and SPI have remained above 0.95

Comments:

- Instrumentation and Controls, and Delivery Ring rf, and external beamlines are relatively standard systems at Fermilab; many of them similar to work that is being done on g-2 or on muon campus AIP projects. The committee believes that these systems are in good shape, have sufficient design maturity, and ready to proceed to CD-3.

Comments:

The remaining four L3 subsystems are very challenging, these are:

- Controlling beamloss in an enclosure that was designed for much lower beam power, (8kW vs 13W)
- Slow spilling the beam out of the accelerator in this enclosure in a way that does not generate beam loss, and provides a good basis for beam extinction
- Providing beam on target with extinction between pulses at the level 10e-10
- Designing a target that can handle the 8kW beam power with a life time of at least a year.

Comments:

- **Beamloss** issues in delivery ring: Extensive modeling has been done. Additional shielding is being installed in key locations, particularly near the slow extraction septa where losses are expected. A (TLM) total loss monitor has been designed, for the delivery ring, and eight TLM systems of this design have been installed in the booster. Further shielding can be installed if operation indicates it is needed.

- **Slow resonant extraction** has also been well simulated, with codes looking at the spill process and codes addressing longitudinal dynamics. The modeling shows that the extinction and beamloss requirements can be met, however these codes are not well benchmarked, particularly for extinction. A new style of extraction septum is being designed and built for this application. The design is based on experience at JPARC, and there has been good interaction between the mu2e project and JPARC. If requirements cannot be met, further improvements to spill quality can be realized using fast quadrupoles (QXR)

Comments:

- **Extinction and Extinction monitoring** has progressed with better understanding of upstream collimator locations. Additionally, based on the design review the project has moved up the design of the AC dipole. Simulation work continues, in particular including realistic errors. The extinction monitor design appears to be sound.
- **Target and remote handling** has received R&D work. Efforts have been underway to ensure a one year life time for the target. (There is a scheduled annual shutdown for other reasons, so a one year lifetime is desirable). This work has looked at various target coatings, but as of this time the baseline target has no coating. Some target R&D work remains, primarily engineering detail. Target station and remote handling work appears to be in good shape.
- All four of these areas are of sufficient maturity to proceed to CD-3.

Comments:

- The first of these three “high challenge” areas are coupled and uncertainties remain regarding achieving full requirements. We encourage Mu2e to do everything possible to understand these uncertainties.

Recommendations:

1. Take every opportunity, at Fermilab or elsewhere to bench mark or test these systems (e.g., there will be 8 GeV operation during g-2 commissioning that could inform beam loss issues for Mu2e)

2. Ensure resources are available to continue simulation efforts on all issues related to delivery ring beamloss and extinction. This work should continue throughout the project phase and into commissioning and utilize any new data available such as what might come from the above recommendation. Specifically, the following should be investigated:

   - Beam losses in the delivery ring
   - The sensitivity of the extinction system to beamline lattice imperfections
   - Continued study of possible mechanisms in the Recycler and Delivery Ring by which beam could end up outside the 250 nsec beam window

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review?

Yes.

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work?

Yes.

6. Is the documentation required by DOE Order 413.3B for CD-3 complete?

Yes

7. Are there any outstanding issues that need to be addressed?

Yes, design optimizations need to be finished to allow the engineering designs to be completed.

- Findings
  - The Muon Beamline WBS is a diverse set of elements including:
    - Vacuum System, Collimators, Upstream External Shielding, Muon Stopping Target, Muon Stopping Target Monitor, DS Internal Shielding, Muon Beam Stop, Downstream External Shielding and the Detector Support & Installation System
  - Considerable progress has been made since the CD-2/3b review
  - The Muon Beamline BAC is $19.8M and design is 65% complete
  - The Muon Beamline interfaces with all other technical systems and the team is working actively with their peers to identify and detail interfaces and to progress the design
  - Many of the designs are awaiting input from other systems in order to complete. However, work to go is well understood
  - Risks associated with the remaining design effort appear to be well understood, managed and tracked
  - The vacuum system underwent an independent external design review in March 2016
  - Other technical designs will not receive a formal external review and will rely on in-progress reviews and a construction readiness review (CRR) prior to releasing procurements
  - All analyses supporting design are written up formally and reviewed independently
  - To support the design process the team has built prototypes and mock-ups in areas where there were technical concerns
  - Installation sequences are at the preliminary stage but are well understood
  - All recommendations from the CD-2/3b & Director's CD-3c review have been addressed

- Comments
  - Very competent, lean, team responsible for the beamline design.
  - The design is 65% complete overall, all systems apart from one are at the 50 – 75% level. There is ample float in the schedule and the resources are being well managed. However, design completion on systems that require input from other systems is lagging; this is not an issue at present but may become one if physics optimizations are not completed in a timely manner.
  - The vacuum system had a successful external review in March this year. Concerns raised at the CD-2/3b review regarding thin films of oil on the tungsten target surface due to the use of diffusion pumps have been addressed and based on work carried out by the vacuum team a decision has been made to go ahead with this option. The target group are fully aware of this decision.

- Comments, cont'd
  - The beamline team does not plan to have any external reviews for the remaining systems and will rely on in-progress reviews and the construction readiness review process in-lieu of formal design reviews. They have made excellent use of prototypes to mitigate potential design flaws that may have been missed.
  - The team should strongly consider a formal review for any of the more complicated designs that have not been prototyped.

- Recommendations
  - Proceed to CD-3.

2.2 Superconducting Solenoids

S. Prestemon, Mark Bird, Dave Koppenaal
Subcommittee 2

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review?
Yes

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work?
Yes, with a couple of exceptions on the TS solenoid cryostat

6. Is the documentation required by DOE Order 413.3B for CD-3 complete?
Yes, most solenoid elements are at or beyond 80% level, with the exception of the TS cryostat.

7. Are there any outstanding issues that need to be addressed?
No, with exceptions related to (2) above.

Findings

- ***The team seems to be functioning well and is well-integrated into the overall project.***
- ***The team has done an excellent job in producing conservative magnet designs and developing a solid procurement strategy.***
- **The solenoid sub-system is a complicated set of 4 superconducting solenoids: 2 straight (Production Solenoid, PS, and Detector Solenoid, DS) and 2 curved (Transport Solenoids, TSu and TSd, partial toroids).**
- **The superconducting magnets are roughly 40% of the total project budget.**
- **The magnets are based on NbTi Rutherford cables co-extruded with Al-stabilizer. This technology is well-developed and has been used for a number of detector-magnets, recently the LHC detectors: CMS and ATLAS.**
- **Simulations looked at fairly large random errors – little influence on physics performance.**
- **Physics is more sensitive to rotation than translations.**
- **TS Conductor ordered & received (44 km ordered; received 45 km).**
- **The contract for TS test units exists. Test units will be tested at FNAL.**
- **Coil modules will be tested individually, i.e. ~3 or 4 coils in series at a time.**
- **Both FNAL and vendors preferred ultrasonic welding of Al conductors as apposed to solder joints.**

Findings (Continued)

- Joint resistance has been measured, below nOhm. They did not measure RRR.
- QP detection has 2 levels of redundancy.
- Switching is performed with IGBTs, with one level of redundancy
- (Add statements of % complete for various packages?)
- TS Magnet assembly equipment 50% design complete.
- Cold mass tooling design is >80% complete; drawings started.
- TS cryostat design is to be finalized at FNAL. Components of cryostat are to be commercially fabricated.
- TS cryostat and test-units will be assembled and tested at FNAL. TS cryostat is behind schedule due to lack of personnel in the past. This seems to have been corrected and progress is being made.
- It is not clear that the all TS test-units can be tested within the time allowed by contract for acceptance.

Findings (Continued)

- **A contract has been issued to General Atomics for final design and construction of PS & DS magnets based on understanding that construction would occur in Poway, CA where the ITER Central Solenoid Modules are being fabricated. Since then GA has not been able to get permission from DOE-FES to use impregnation equipment in Poway and now plans to fabricate at the Tupelo, MS facility. The Tupelo facility makes rail-guns for the navy, but has not built superconducting magnets. FNAL and GA technical personnel would like to perform more tasks to demonstrate procedures and equipment and train personnel prior to fabricating real coils. GA management sees this as a Change Order and is considering change in cost to perform this work.**
  - If GA had originally proposed using Tupelo facility, contract may have been awarded to one of the other qualified vendors. If GA wants to switch sites, they need to qualify equipment, procedures, personnel.
- **Contract included cold-test of PS & DS at Poway and high-current-testing at FNAL. If fabrication is to be done at Tupelo, GA is willing to ship PS & DS to Poway to perform cold-test. However, typically one energizes a magnet at the factory so, if there are problems, it can be repaired prior to shipping.**
  - Magnets cannot be cold-test at Tupelo. If they are tested at Poway and problems arise, the magnet might need to be shipped back to Tupelo.
  - Testing by GA would eliminate the need for two cryogenic setups at different locations at FNAL.
- **Protection system has a large degree of redundancy and is being developed by an appropriate, experienced team.**
- **The cryogenic support system making good progress by experienced team.**

Comments

- **The buyer/seller relationship within the magnet contracts is critical to the success of the project. The team should continue to be vigilant in maintaining strong vendor oversight, including on-site monitoring, without active participation that dilutes vendor responsibility in production, QA, and schedule.**
- **Develop and finalize the plan for vendor development articles for PS and DS, taking into account technical risks perceived by both the vendor and project technical experts. The plans should focus on risk reduction while minimizing schedule impact.**
  - Evaluate in particular the skill experience of the Tupelo site in large scale coil fabrication techniques and processes, and to perform large scale VPI
- **Finalize the plan for cold-testing. Priority should be on risk mitigation and schedule. The project should evaluate the cost and schedule benefit of performing all cold tests at FNAL; this includes quantifying the cost-recovery from the vendor contract.**
- **Verify that there is ample time in the schedule to perform the acceptance tests for each magnet, per the vendor contract.**

Comments (Continued)

- Evaluate superconducting bus quench scenarios to verify that there is ample stabilizer/cooling under all fault scenarios
- Investigate carefully the fault scenario of modest vacuum loss in conjunction with a magnet quench; in particular the resulting increased possibility of arcing. Is Paschen-testing necessary?
- Finalize the use of cones / plates between the four magnets instead of bellows.
- The project is planning to use detailed model analysis to predict the waveform from impulse tests as a means of qualifying magnets electrically. Consider the use of impedance spectrum testing after each layer as an alternative.

Recommendation

- **Ensure that the appropriate technical resources are available to complete the TS cryostat design and support the project through the TS cryostat CRR, scheduled for January 2017.**

- **Finalize the TS cryostat design and perform an in-depth technical review prior to initiating procurements of cryostat components.**

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review? **Yes**

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work? **Yes**

6. Is the documentation required by DOE Order 413.3B for CD-3 complete? **Yes**

7. Are there any outstanding issues that need to be addressed? **No**

- **Findings**
  - Vertical slice tests of straws, supports, preamps, analogue MB (Mother Boards), digitizers & ROC (Read Out Control) have been done piecemeal, awaiting final prototypes. Concepts are well tested.
  - Problems with panel construction and gas manifolds led to redesign, schedule delays, and cost changes.
  - Parts will be ready for an assembly prototype construction soon. This will be a final prototype before the CRR (Construction Readiness Review).
  - Extensive tests of the straw production and performance demonstrate readiness to proceed with the CRR and production purchase.
  - Panel mounted readout electronics has evolved to a more compact and usable design, incorporating both digitizer and ROC, called the DRAC (Digital Readout Assembler and Controller). This results in slight delays and necessitates a final prototype.
  - CRRs will be conducted for straws (8/2016), assemblies (8/2017), and electronics (2018).

- **Findings (cont'd)**
  - Recent variances in cost and schedule for the assemblies (475.6.3) and electronics (475.6.4) were the results of problems mentioned above.
  - Final design of gas distribution and power connections on the panels remains to be completed.
  - Alignment has been well planned with a comprehensive series of measurements of sense wire positions and fiducials that should result in a final mechanical wire position accuracy of about 100 μm.
  - An extensive and extremely detailed simulation has been produced which accounts for all pertinent aspects of detector background, pulse rates, and electronic signal development. This simulation agrees with lab measurements of straw tube resolution and timing.
  - Straw tubes with a similar gas mixture, operating in ATLAS at the rates similar to those expected from the Mu2e beam flash, did not experience continuous discharge conditions.

- **Findings (cont'd)**
  - No comprehensive plan for aligning the detector with tracks has as yet been developed.
  - Assembly production logistics are complicated and spread over many sites, but careful coordination and bookkeeping mitigate risks.
  - Plans have been developed for detailed QC (Quality Control) and the documentation of performance and construction details for each straw.
  - Straw and panel construction will depend on undergraduate labor at the collaborating institutions. Previous experience at those institutions has been very favorable, and sufficient contingency has been allocated for the unlikely case of manpower shortages.
  - Level 3 managers are usually different people than the CAMs (Control Account Managers) for Level 3.
  - The CAMs have actively investigated and resolved variances at the activity level

- **Comments**
  - The tracker team is highly competent and very collaborative.
  - The experience garnered with NA62 that utilized a large straw system in vacuum is a proof of the principle of the Mu2e straw design.
  - The Tracker Oversight Committee, consisting of experts external to Mu2e, has had an active and helpful role in constructively reviewing the Mu2e tracker design.
  - The committee fully supports complete testing of a larger statistical sample of straws and straw tube detectors for radiation damage, from radiation aging effects (from integrated current draw) and from neutron irradiation.
  - The committee also supports post-mortem analyses of highly irradiated straw tube detector components, including the cathode metallization and the sense wire.
  - It is useful to develop robust designs for shipping containers including environmental monitoring during transit between construction sites.
  - We encourage publication of the excellent simulation system and results.

- **Findings**
  - The Experiment changed the baseline from BaF_2 to undoped CsI crystals and from a solar-blind APD (Avalanche PhotoDiode)to UV extended SiPM (Silicon PhotoMultiplier) photodectectors in December 2015.
  - The new baseline meets all the physics requirements of the experiment.
  - The design is 83% complete.
  - The plan is to launch the procurement of pre-production crystals and photodetectors in June 2016.
  - A Final Mechanical Design Review is planned for October 2016.
  - A “Module 0” beam test is planned for November 2016.
  - It is anticipated that a Construction Readiness Review (CRR) for the crystals and photodetectors will be held in December 2016 and a CRR for everything else will be held in April 2017.
  - A Memorandum of Agreement is close to being approved by the Italian funding agency as documented in the Key Assumptions document.

- **Findings (cont'd)**
  - The goal is to have 20 channels per Wave-Form Digitizer (WFD) card, but there is a risk that only 18 channels can be accommodated because of the FPGA resource availability.
  - The current cumulative CPI is 0.72, which is low. It was explained that it was because the baseline changes to CsI and SiPM have not been incorporated in the EVMS system and some of the R&D activities carried out at Caltech are not yet in the budget.
  - The Calorimeter Group have found out that with the expected exposure to neutrons on the inner part of the detector, SiPMs will develop large dark currents which cause unacceptable noise. They will mitigate this problem by running the entire detector at 0 C.
  - Risks are being actively managed.
  - The contingency/risk for the price of the crystals is handled by taking the highest of the budgetary quotes instead of the middle or lowest, and adding 15% as the contingency.

- **Comments**
  - Once the baseline changes are included in the EVMS system, CPI should be much closer to 1.
  - The mitigation method for the increased dark currents does not have a large margin of error, but because the large neutron flux region within the detector is small (~100 crystals out of 1400), even in the worst case, most of the detector should perform at full capability
  - We reiterate this important idea from a previous review: The Module 0 test should evolve into a full system test, and include as many final components as is possible.
  - The specifications for the crystals are carefully set to strike a balance following value engineering practice.

- **Comments (cont'd)**
  - The crystal light output specifications are documented in a somewhat confusing way partially because they use different descriptions in different documents. The crystal specification document specifies it in terms of the number of photo-electrons using a specific photo-multiplier tube (the model number is currently missing), while in the QA/QC document, it is specified relative to the light output from a calibrated standard crystal which will be provided to the vendors. We understand that they are equivalent, but if anything, the specification document, which is presumably given to potential vendors should use standard crystal, while the QA/QC could use a criterion based on the number of photo-electrons.

- **Comments (cont'd)**
  - The U.S. should do everything possible to ensure that the significant Italian contribution to the experiment as detailed in the MOA is finalized.
  - The calorimeter group is inclined to connect three SiPM chips in series. They claimed that the detector capacitance is reduced by a factor of three by this method (which reduces electronics noise) while the signal size triples (relative to the single chip case). We believe that the signal size will be the average of the three SiPM, not be the sum of the threeand therefore stays the same as the single SiPM case. They should study this issue and its implications (there may not be any) carefully.

- **Comments (cont'd)**
  - With three SiPM chips connected in series, when one of them is damaged heavily, study if the other two will produce a useful signal.
  - If they do produce a useful signal and if the deterioration of the third is not noticed, the damaged SiPM will take a smaller fraction of the total bias voltage, and as a result larger fractions of the bias voltage will be born by the other two healthy SiPM chips. The group has done an initial study of this with encouraging results. Further studies will continue.
- More frequent and meaningful milestones would be useful to be visible in P6 for the work being done in Italy.

- **Findings**
  - The Cosmic Ray Veto (CRV) is a large array of scintillation counters surrounding the detector and a portion of the downstream transport solenoid.
  - CD2 Recommendation 9 asked that collaboration complete their detailed simulation campaign to determined required efficiencies, dead time, and their radiation environment. This was impressively completed by the Collaboration.
  - The extensive high-statistics background simulation campaign with conservative detector geometry assumptions including dead regions, benchmarked readout response models, and full event reconstruction has provided detailed specifications of the CRV efficiency, coverage, and radiation tolerances. Their conclusions are in reasonable agreement with prior, less sophisticated, calculations and refine their specifications.
  - These simulations show that in a few locations, near required CRV penetrations, the coverage can be slightly increased to further reduce the calculated 0.2 event background estimate over the planned experiment live time. These are being incorporated straightforwardly into the final CRV design.

- **Findings (cont'd)**
  - The CRV is based on extruded plastic scintillator with a co-extruded reflective cap that is read out by wavelength-shifting (WLS) plastic optical fibers, a well-established technology at Fermilab.
  - The readout is based on SiPM photodetectors and electronics that leverage ultrasound technology and electronic components that are commercially available and mounted on custom boards.
  - Efficiency specifications, derived from the detailed simulations, have been are used to specify the required light yields for the system.
  - Test beam measurements using prototype scintillator modules show that the latest iteration of prototype scintillator extrusions, and WLS fibers, significantly exceed the refined specifications for light yields.
  - The latest iteration of prototype scintillator extrusions also meets their outside and fiber-hole dimensional tolerances.

- **Findings (cont'd)**
  - SiPM response and dark noise tests with the planned devices have been shown to meet specifications.
  - Radiation testing of photodetectors has demonstrated adequate radiation hardness using lower-energy protons that model expected neutron interactions. Radiation hardness tests using neutron exposures are planned prior to procurement.
  - The readout team's plan for single event upset mitigation is based on vendor recommendations and appears reasonable.
  - The methods, fixturing, and procedures for CRV module assembly are well advanced with a number of completed mechanical and optical prototypes.
  - The UVA-based module assembly task is working closely with their local safety apparatus on the specific concerns at their factory site including chemical exposure, repeated operations, materials handling, and machine tools.

- **Findings (cont'd)**
  - Labor estimates for CRV module assembly, which have now been augmented by multiple prototypes using pre-production fixturing, appear reasonable and validate earlier calculations. They will be further refined during the planned prototype assembly later this year.
  - CD2 Recommendation 8 asked for full vertical-slice tests of each subsystem from detector component through the DAQ/readout before CD3c. The Trigger/Data Acquisition (TDAQ) and CRV have agreed, on preliminary data and control protocols through the optical link interface. They have read out mock data from the TDAQ buffer with a pilot TDAQ system, and they plan a TDAQ/CRV vertical slice test at the Fermilab Test Beam Facility using pre-production electronics this Summer prior to planned Construction Readiness Reviews. While this is not precisely the sequence envisioned in the recommendation, the Committee considers their TDAQ integration tasks to be at a satisfactory at this stage of the design.

- **Findings (cont'd)**
  - Installation of the full CRV and its support structure are not within the project scope, but the design, procurement, and fabrication of the structure, the design and fabrication of installation fixturing, their prototype installation tests, and a external installation of a portion of the CRV on a temporary support structure are part of the project. These tasks and the planned post-project installation are not particularly exotic, but will require detailed collaboration between the task and the project safety team to ensure the installation phase is successful.

- **Comments**
  - The project safety team and the CRV task are encouraged to conduct a site visit coinciding with the start of their planned prototype module production scheduled for Fall 2016. They should demonstrate/evaluate that the methods, fixturing, and procedures for CRV module assembly is efficient and safe.
  - The recent adoption of the NOvA polishing (fly-cutter) machine is a welcome step in moving towards safe full-scale production stations, and similar upgrades could be considered as refinements for other cutting operations.
  - Radiation hardness testing using neutron exposure tests are planned prior to procurement. The Committee notes that it will be reassuring to complete the neutron radiation hardness testing prior to procurement.

- **Findings**
  - The TDAQ system covers the hardware, software, firmware and networking from the system specific Read Out Cards (ROCs) up to the event building and data storage networks. The system also distributes precision timing information to and control information to and from the sub-system ROCs.
  - The requirements are backed by a sophisticated simulation that covers both computational and bandwidth requirements.
  - The TDAQ system is composed almost exclusively of commercial hardware:
    - Data Transfer Cards (DTC) – PCIe FPGA engines with high speed data inputs
    - Servers
    - A single Control Fanout Module (CFO) plus fanouts that handle timing and fast control including providing 48 bit event tags
    - Networking equipment.

- **Findings (cont'd)**
  - The TDAQ system is built on a data pull model with data flow initiated by the Run Control Host via the CFO.
  - The basic link speed is set to 3.215 Gbps.
  - Subdetectors, not the TDAQ are responsible for ROCs and signal paths within the solenoid vacuum.
  - The only custom hardware design in the plan is a simple, largely passive, FMC card to provide clock and fast control connectivity to the CFO instantiated on a commercial PCIe card (same card in CFO and DTC).
  - A sophisticated "run plan" memory is included on the CFO card to allow complex interleaving of run conditions on a spill by spill basis.
  - The DTC card has significant compute power that can be used for preliminary data filtering.

- **Comments**
  - The basic architecture seems to be well thought out and there is significant, if not generous, margin against expected bandwidth and compute requirements. There are also possible mitigations both in terms of bandwidth (run at higher link speed) and compute power (increase the number of servers by ~30%).
  - Many failure modes and possible challenges have been thought through and mitigation strategies have already been developed in many cases.
  - The team is strong and has significant experience and expertise and is likely to be able to respond quickly to any problems which may develop in testing and commissioning.
  - The team had not fully considered the implications of giving “data” absolute priority over “control” on a shared link but quickly developed a plausible work around in real time during the course of the review – a positive indicator.

- **Comments (cont'd)**
  - The hardware procurement plan is dominated by two large purchases –
    - General purpose commodity "server" class computers
    - Commercial but very specialized PCIe based FPGA cards that are used for the DTC and CFO
  - The servers are planned to be purchased about 1 year after the PCIe cards on the expectation that the servers are much more of a commodity item and present no schedule risk. This seems reasonable.
  - The PCIe FPGA card purchasing plan does not seem to be fully developed yet. Delaying purchase of these cards could save costs but since the market is small, any "new" card, even from a trusted vendor, needs to be carefully evaluated to be certain that it can deliver the required performance. A contract that obtained a few cards early with an option for the full number later, if the first cards are satisfactory could be attractive.

- **Comments (cont'd)**
  - The present baseline strategy of simply purchasing all needed cards a year early to allow time for delivery and test may not be optimal. It may also be important to understand where the procurement sits relative to the FPGA manufacturer's development cycle – buy too late in an FPGA development cycle risks using obsolete and unsupported tools during most of the experiment while buying too early risks procurement delays and tool instabilities.
  - The extended Mu2e schedule is not well matched to the Xilinx development cycle and some care may be needed to optimize the time at which purchases are actually made.
  - This same short FPGA and PCIe cycle implies that the project will want to ensure that the number of cards purchased will be sufficient for the lifetime of the system.
  - Short life cycles are not likely to be a problem for the servers or network equipment

- **Comments (cont'd)**
  - The TDAQ had participated in "vertical slice test" efforts at some level with all three major detectors – Tracker, Calorimeter and CRV but only in the case of the tracker were real detectors sending real data through the TDAQ structure into data storage. In the other cases simulated data was provided to the TDAQ structure. In all cases full timing and slow controls paths remain somewhat untested and it seems likely that further vertical slice testing with more complete systems would be useful in the near future.

- **Recommendations**
  - Conduct a full system test for each subsystem prior to the respective procurement readiness review.
  - Complete a comprehensive system test of the first plane to provide input for the straw assembly CRR, currently scheduled in August, 2017 (WBS 475.6, Tracker).
  - Develop plans to monitor and control gas temperature and pressure in the tracker (WBS 475.6, Tracker).
  - Ensure that the documents for detailed assembly and installation procedures are complete by the final mechanical design review. (WBS 475.7, Calorimeter).
  - Proceed to CD-3.

Charge Questions

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review?

   Yes, (no conventional facilities related recommendations outstanding)

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work?

   Yes, conventional facilities design was completed as part of CD-3b

6. Is the documentation required by DOE Order 413.3B for CD-3 complete?

   Yes, conventional facilities documentation was completed as part of CD-3b

7. Are there any outstanding issues that need to be addressed?

   None

- **Findings**
  - conventional facilities is currently over 75% complete and SPI = 1.13 and CPI = 1.05 for April 2016
  - A previous period where contractor schedule performance had fallen behind in Nov-Dec 2015 was resolved by replanning and performance has since improved
  - Construction safety has been very good. There was one injury due to a rebar foreman slipping on a rebar cage and breaking their wrist but did not result in a lost time injury. The project implemented enhanced programs after the incident which have been effective.
  - Beneficial occupancy for the Detector Bldg is scheduled for November 2016 and there are at least 3.8 months of float beyond that date before technical work would be impacted
  - Field change costs to date are $1.1M and are largely due to technical changes, primarily the remote handling system change and a strategic contract addition that reduced construction oversite costs. Errors and omissions costs are negligible.
  - conventional facilities budget has been reduced from its original allocation and current BAC is $20.6M and EAC is $19.9M. Contingency on work to go is estimated at 12%
  - A Transition to Operations Plan has been prepared for the conventional facilities

- **Comments**
  - Conventional facilities construction has made outstanding progress, currently over 75% complete with excellent cost and schedule performance (SPI & CPI >1)
  - The Project has an experienced and high performing conventional facilities team in place and resources are adequate to deal with remaining conventional facilities activities
  - The complex structural concrete work in the Detector Building, which is the most technically challenging conventional facilities work, is completed and remaining work is relatively straight forward
  - The Detector bldg. is enclosed and will be weathertight by late June leaving remaining interior fit-out less vulnerable to delay, therefore beneficial occupancy on or ahead of schedule in November is likely
  - The construction safety program is robust, but will require continued planning and oversight diligence as interior fit-out progresses due to potential crowding of trades in limited interior space

- **Comments cont'd**
  - Technical design is at ~85% complete so change risk to conventional facilities going forward is moderate but, technical equipment needs and shielding requirements often change late in conventional facilities construction, which can lead to unforeseen conventional facilities changes
  - Conventional facilities engagement in the technical integration process thus far has been commendable and will be critical going forward
  - Current conventional facilities contingency allocation of 12% on work to go appears low given potential for technical changes impacting conventional facilities, however project contingency reserve is adequate to cover some overrun here
  - The Commissioning contractor should review and comment on design drawings while there are opportunities to make low-cost changes to interior system fit-out that will improve maintainability and system monitoring, test and start-up capability

Recommendations

- **Proceed to CD-3**

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review?
   Yes

5. Are the ES&H aspects being properly addressed, given the project's current stage of development?
   Yes

6. Is the documentation required by DOE Order 413.3B for CD-3 complete?
   Yes

7. Are there any outstanding issues that need to be addressed?
   No

Findings

- Documentation supporting CD-3c is complete, updated and signed-off
  - HAR, SVAR, NEPA and ISMS plan
- The Project Management Plan (PMP) was updated and well defines the ESH&Q roles, responsibilities, authorities and accountabilities for staff on the project team
- Recommendations from the previous review have been well addressed. Notably:
  - Hiring of well qualified and knowledgeable ESH & QA staff
  - Updating documents to reflect all risks
- Project team is established, mature and working well together, ESH staff are embedded in the Project organization and Project has access to capable institutional ESH resources.
- ESH&Q for all facets of the Project are adequately addressed and ready for CD-3C

Comments

- Total Loss Monitor (TLM) system has been approved for use as a credited engineering control to monitor and act on excessive beam losses
- Passive Shielding requirements have been updated and implemented through construction efforts
- ESH&Q site visits to vendor facilities and partners (labs and universities) are planned
- ESH discussed in all presentations, along with progress to Construction Readiness Reviews
- Design Completion Definition, Mu2e Quality Assurance Program and Mu2e Quality Planning documents are signed off
    - Documents establish the uniform general requirements for the design completion of the different components of the Mu2e project & provide guidance for assuring that the quality of work will meet the expectations

Comments

- ODH analysis submitted to the Muon Cryogenic Safety Committee (sub-set of Institutional Committee)
- An established Operational Readiness Clearance process is in place that provides a path for ESH review of experiments, projects, and R&D efforts prior to operation
- Well developed ESH plans to control radioactive gasses, contamination and water activation were discussed for the Target Handling and Target Design activities

Caution:

- While Incident/Accident rates remain good, there remains concern that some project personnel stated that there are not unique hazards with this project and that ESH risk is very low. (We've been doing this at FNAL for years now!) We would caution against complacency or drifting from good conduct of operations. Effort should be applied to ensure hazards and mitigations remain visible and well understood. This includes a strong implementation of the institutional Work Planning and Control program for all aspects of installation and testing.

Recommendations

- Proceed to CD-3

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review? Yes

3. Are the current project cost and schedule projections consistent with the baseline cost and schedule in the Project Execution Plan (PEP). Is the contingency adequate for the risks? Yes

6. Is the documentation required by DOE Order 413.3B for CD-3 complete? Yes

7. Are there any outstanding issues that need to be addressed? No

Findings

- The Total Project Cost (TPC) remains at $273.7M and the CD-4 date remains at Dec 2022.
- As of the end of April 2016 the project is:
  - 45.7% complete
  - $44.5M of cost contingency (36.2% to go).
  - 22 months of schedule contingency (40% to go).
  - $31M in estimate uncertainty
  - $5.7M in 80% confidence level risk
  - $103.7M work completed
- At baseline in March 2015 the project was:
  - 27.4% complete
  - $52.5M of cost contingency (32.7% to go)
  - 24 months of schedule contingency (35% to go)
  - $46.2M in estimate uncertainty (from Dec 2014)
  - $6.5M in 80% confidence level risk (from Dec 2014)
  - $60.6M work completed

Findings

- The current EAC is $5.1M higher than the BAC, $2.3M of which is the cumulative cost variance. Solenoids make up $2.6M of the EAC increase. A bottom's up ETC was completed in March 2016 and the contingency remaining based on the ETC is $41.7M ($32.5% to go). A bottom's up ETC is completed annually and updates to the ETC are done monthly as needed.
- The ETC increase of $11M since baseline is spread out relatively evenly among the major systems ($2.2M – Project Management, $2.3M – Accelerator, $1.3M Conventional, $4M – Solenoids, $1.4M – Cosmic Ray Veto)
- An SPI downtrend was caused by resource shortages mainly in the cryo engineering area that have since been addressed.
- The project CPI and SPI are 0.98 and 0.99 respectively.
- The project has developed a preliminary contingency spend down plan.
- The project has utilized EVMS for approximately 24 months.
    - The SC March 7-8, 2016 EVMS Surveillance Review stated that the "FRA EVMS still meets the requirements and intent of the ANSI/EIA-748 standard.

Findings

- Overall design is at 85% complete with the conventional construction at 100% and the Muon Beamline at 65%. The rest of the components are within 80% to 90% complete
- The project has been progressing on the CD-3a and CD-3b long lead procurements
  - CD-3a approval in July 2014 – TS and DS solenoid conductor accepted, PS conductor to be delivered in the Fall with 2 months of float.
  - CD-3b approval in Mar 2015 – Detector Hall is 75% complete but Beneficial Occupancy has slipped about 6 weeks. The schedule slipped due to poor weather, a labor strike, changes in remote handling and other technical integration issues. This delay did not affect the overall schedule since there was adequate float on this activity. TS Coil Module contract in place.
- Since baseline in March 2015, the risk registry has had approximately 62 updates (39 modified, 11 added, 9 retired, and 3 realized).
- The early completion date is Feb 2021 which leaves 22 months in schedule contingency (40% to go). 2 months in schedule contingency were used since baseline.

Findings

- The project schedule contains 1,203 milestones and 7,396 activities of which 4,074 are complete.
- The critical path goes through fabrication, installation, and commissioning of the PS and DS.
- CD-3 is needed by September 2016 in order to initiate construction of the PS/DS to avoid delay in the overall schedule.
- Given the remaining risks, the project has performed a Monte Carlo analysis that shows project completion in April 2022 with 80% confidence. If the project is completed in April 2022, the project would incur an additional $4.9M in cost which equates to approximately $350k in monthly standing army costs.
- Total estimated contingency need is $41.6M (Estimate Uncertainty + 80% Risk + Burn rate from schedule risk).
- Major risks remaining include Fermilab overhead rates, need for additional tracker stations, and Magnet fabrication issues.
- The project has 33 procurements >$500K totaling $61M.

Findings

- The necessary GPP projects are substantially complete and most the remaining AIP projects (Beam Transport, Recycler RF, Delivery Ring, Shield Wall) needed for the project are scheduled to be completed this summer, well before the Mu2e need by date.
- The Cryo AIP currently has a forecasted completion date of 7/15/2017 and a 9/15/2017 need by date.
- Since baseline there were a total of six level 2 milestones that were all completed on time.
- The PS/DS solenoid vendor at the end of 2015 notified the project that fabrication of the solenoids would move from Poway, CA to Tupelo, MS. The project is negotiating additional practice windings, potings, and insertions with the vendor to increase the likelihood of vendor success. Initial estimates for performing these actions would cause an additional 2-4 months to the overall schedule and $200 – 400K in cost. An itemized breakdown from the vendor will be evaluated by the project to determine if the added cost/schedule to the project is worth the mitigation action.

Comments

- The project has performed well since the last DOE review. Since the March 2015 project baseline, $43.1M of work has been completed and $123.2M of work remains. During this period, $8.0M in contingency was used. The ratio of contingency used to work completed since baseline is 18.6%.
- All six level 2 milestones since baseline have been completed on time.
- The performance during this period allowed the to-go cost contingency percentage to increase to 36.2%.
- Since Dec 2014, the combined estimate uncertainty and 80% CL of cost risk remaining was reduced by $16M from $52.7M to $36.7M. During this period, $11.7M in contingency was used which is a positive trend. At this usage rate, adequate contingency is available to meet the current estimate uncertainty and risks.
- However, after factoring in the current management ETC which increases project cost by $2.8M, the project is performing just about at the level it needs to in order to complete the project. If a BCR was processed to incorporate the ETC, $41.7M in cost contingency would remain.

Comments

- Using ETC, the ratio of cost contingency used to work completed since baseline (25.1%) is not as favorable a trend. At this rate, all of the remaining contingency ($41.7M) will be required to finish the project.
- The project has an estimated $41.6M in cost contingency need (Estimate Uncertainty + 80% Risk + Burn rate from schedule risk). With $41.7M in cost contingency (factoring in ETC) remaining, this appears appropriate at this stage of the project.
- At this time the committee believes there is adequate cost and schedule contingency remaining to successfully complete the project. However, if risks are realized at a higher then anticipated cost impact, the project could quickly find itself with unsustainable contingency draws.
- The committee commends the projects use of EVMS as a project management tool. The CAMs are providing useful information and analysis to help successfully manage and complete the project.
- The committee also commends the project on actively managing risks. The remaining risks on the project appear comprehensive, complete, and well understood.

Comments

- The one prior Cost and Schedule recommendation from the February 2015 DOE review was completed.
- The schedule has been analyzed through Deltek Acumen Fuse software. The project uses this as a tool to improve schedule integrity, which is a good practice.
- The project has entered its peak workload period which continues through project completion. Significant effort and diligence to complete the work on schedule is needed in order to finish the project in the early completion timeframe.
- The project team should be vigilant to maintain and preserve the current schedule and cost in order to provide sufficient time/cost contingency to react to delays/mishaps that may occur in the technically complex scope remaining. Good project performance can also lead to adding scope contingency which enhances the overall project.
- The project is also entering a crucial period where procurement and activity delays can potentially push back project completion. PS, DS, and TS activities as well as detector system activities are all on or near critical path, so delay in many of the parallel project activities could result in a delay in overall schedule.

Comments

- Labor represents approximately half of the remaining project cost so delaying project completion results in significant standing army costs (up to $350K a month).
- Using cost contingency to mitigate cost and schedule risk is a good idea especially when that activity is on the critical path and has significant risk. If the PS/DS vendor fails to complete the solenoid using the conductor provided, then there is a potential for a 1 to 2 year delay to procure more conductor.
- Continue to pursue and execute the solenoid risk mitigation measures in order to minimize overall schedule impact.
- In regards to the solenoids, consider having the management, technical, and procurement teams reach out as necessary to other national labs who have recently managed complex magnets in order to help resolve the current technical and vendor management issues.
- The committee commends the proactive approach to managing the PS/DS solenoid vendor. Onsite presence and pursuing mitigation strategies will benefit the project to stay on schedule and partner with the vendor for successful magnet delivery. That being said, management attention on the remaining procurements and proactively managing vendors will be essential to completing the project on schedule.

Comments

- Currently the project is using payment milestones to track solenoid vendor progress, and a more detailed vendor fabrication schedule will be submitted and approved.
- After the vendor schedule is received, ensure the project P6 schedule includes enough granularity to alert management to delays in the solenoid procurements. This could include additional "trigger points".
- The current contingency spend down plan does not include most ROM costs and decision dates. Design by and decision points for in-scope additions/enhancements should be determined for execution within the early completion schedule. Also setting thresholds and determining when the project is in a position to execute contingency spend down items should be established.
- Having a refined contingency spend down plan will help the project be proactive and serves as a planning tool if the project performs well.

Recommendations

- Proceed to CD-3

PROJECT STATUS (April 2016)		
Project Type	MIE	
CD-1	Planned: 4th Q FY12	Actual: Jul 2, 2012
CD-3a	Planned: 3rd Q FY13	Actual: Jul 10, 2014
CD-2	Planned: Mar 2015	Actual: Mar 4, 2015
CD-3b	Planned: Mar 2015	Actual: Mar 4. 2015
CD-3	Planned: Sept 2016	Actual: TBD
CD-4	Planned: Dec 2022	Actual: TBD
TPC Percent Complete	Planned: _46.3____%	Actual: ___45.7__%
TPC Cost to Date	$106.0M	
TPC Committed to Date	$199.6M	
TPC	$273.667M	
TEC	$250.0M	
Contingency Cost (w/Mgmt Reserve) Contingency Cost (w/Mgmt Reserve) based on ETC	$44.5M $41.7M	__36.2___% to go __32.5___% to go
Contingency Schedule on CD-4b	_____22_months	___40__%
CPI Cumulative	0.98	
SPI Cumulative	0.99	

- Team Members:
  - Robert Wunderlich, DOE (retired)
  - Jeff Geouque, ORNL
  - Joe Ingraffia, ANL
  - Stephen Meador, DOE-SC
  - Don Rej, LANL

1. Have the project and the laboratory responded satisfactorily to the recommendations of the previous DOE review?

   Yes, the Mu2e Project has a system in place to record review recommendations and track them through closure. The responses to previous recommendations are complete and well developed.

2. Is the detailed design sufficiently mature and appropriately reviewed so that the project can continue, as planned, with the procurement and fabrication work?

   Yes. Overall, design activities are sufficiently mature to proceed with procurement and fabrication work. However, there remain a handful of subsystem designs that are not complete. Where designs are not 100% complete, the Mu2e Project has plans to complete the designs, while any remaining issues have been identified and are reflected in the risk and contingency analyses.

4. Are the management and resources adequate to deliver the proposed technical scope within the baseline budget and schedule as specified in the PEP?

   Yes, a competent management team is in place and suitable project management systems are being implemented to successfully manage the project. Lab-wide staffing of critical skilled resources remains an issue. Fermilab has mechanisms in place to estimate required project resources and resolve resource conflicts. In any case, continued diligence is needed and this topic should be a standing agenda item for the monthly Project Oversight Group meetings.

6. Is the documentation required by DOE Order 413.3B for CD-3 complete?

   Yes, all the required CD-3c documentation has been completed.

7. Are there any outstanding issues that need to be addressed?

   No

Findings: Project Organization and Staffing

- The Project Execution Plan (PEP) was revised to reflect comments and recommendations from DOE CD-2/3b review. Revisions included management descriptions, KPPs, milestones and transition to operations.
- Detailed responsibilities, authorities, and accountabilities for key project personnel are documented in the PEP. These include the Federal Project Director (FPD), Deputy FPD, Laboratory Director and Deputy Director, the Project Manager, and Division heads.
- Project management positions identified at the CD-2/3b review, such as the ES&H Manager and the QA Manager, were filled by experienced professionals.
- Control Account Managers (CAMs) and other Project staff are deployed by matrix organizations at Fermilab and other institutions. For example, the INFN in-kind contribution to the Calorimeter is being led by the Mu2e Calorimeter Level 2 Manager at LNF. In addition, and MOA is being developed. Consequently, risk levels have decreased from high to moderate since the 2014 CD-2/3b review.

Findings: Project Organization and Staffing (cont.)

- Succession planning is evident. An experienced manager was recruited to replace the Conventional Facility CAM who retired in 2015.
- A systems integration team with broad and deep expertise is in place to oversee integration during installation, commissioning, operations, and to ensure optimal subsystem functionalities.
- Approximately one half of the budget for the remaining project work to go is for materials and supplies. To meet Mu2e and other Fermilab project acquisition challenges, the Fermilab procurement department has increased staffing from 19 to 29, with 5 more hires planned in the next two years.
- Project staffing assignments, from the line organization, are established one year at a time through agreements with Laboratory Divisions and Sections. Agreements for FY17 (and beyond) are under discussion.

Findings: Project Organization and Staffing (cont.)

- Engineering specialties (cryogenics, vacuum, resonant extraction) are in high demand. Schedule variances have frequently been caused by resource shortfalls, resulting in residual risks arising from lower design maturities than planned.
- Universities and foreign Laboratory collaborations are a critical part of the Mu2e project. Current focus is on engineering design. Statements of work are required prior to receiving funding. Progress is reported and included in the project EVMS system.
- A Mu2e Project Management Group (PMG), consisting of the Mu2e Project Manager, Division and Section heads, Laboratory Management personnel, other representatives of Fermilab, meets monthly to coordinate and monitor the progress of the project as well as between the project and the rest of the Laboratory at the working level. The Mu2e Program Manager and Federal Project Director are invited to participate in these meetings.

Findings: Project Organization and Staffing (cont.)

- The use of external experts in project reviews, advisory committees, and acquisition oversight committees (AOC) have increased since the 2014 CD-2/3b review and have led to higher confidence in readiness for CD-3 (e.g., in assessing design maturity).

Findings: Procurement

- Procurement support of Mu2e project is centrally managed by the Procurement Department, which has assigned 2-3 FTEs to support project procurements.
- Since the Director's Review of Project Procurement Support in Aug 2012, the lab has made a concerted effort to increase staffing level to support major projects. The Project Office continues to monitor procurement staffing levels to ensure sufficient staff with the right mix of talent and experience are available to handle the peak periods of contract award/administration.
- The project is utilizing a proven tool, Advance Procurement Plans, for acquisitions above $500k to stay abreast of near term and long term procurements. The project has identified a total of 33 APPs totaling $61M. Of those, 14 APPs have been awarded, and 19 APPs totaling $25.1M remain for FY16-FY20. The Project reported that the APPs are in sync with the P6 schedule.

Findings: Procurement (cont.)

- Laboratory and DOE oversight is required for procurements that exceed identified thresholds. None of the remaining Project acquisitions will require DOE approval.
- The Fermilab Procurement department uses a best value philosophy where decisions are based on weighting of 70% technical and 30% cost.
- The project reported that applicable quality requirements are incorporated into the subcontracts.
- The project has established an Acquisition Oversight Committee to obtain advice on Mu2e acquisitions on at least annual basis.
- Although referred to during the review as an option, the cold testing, priced at $349k, has been included in the base award for the DS/PS subcontract with GA. Therefore, regardless of where the cold test is conducted, there should not be an increase to the fixed price. If the project decides to descope the GA conducted cold test, it will have to be negotiated out of the subcontract.

Findings: Project Management Systems

- The Fermilab Director convenes a monthly Project Oversight Group (POG) with senior Laboratory managers to review the high-level status and health of projects across the Laboratory.
- The Mu2e Project is reviewed regularly by the POG to ensure acceptable performance trends and to provide assistance to Division/Section heads and Project Managers to resolve issues that may threaten project budgets, schedule, or meeting key performance requirements. Standing agenda items include major procurement plans, issues, and status.
- The Project stated that the overall Design is 85% complete, based on criteria established in the Design Completion Definition Document which establishes maturity levels. This approach uses the same methodology as the APS Upgrade Project at ANL.

Findings: Project Management Systems (cont.)

- To ensure that designs satisfy the requirements, and can be successfully fabricated and function to specification, the Mu2e Project relies on a series of Final Design Reviews. These design reviews provide an independent assessment of the likelihood that systems will meet their technical specifications and perform as required. The Mu2e Project follows a graded approach described in the Fermilab Engineering Manual where high-risk systems require more independent scrutiny than lower risk systems.
- The Project has scheduled a number of Construction Readiness Reviews prior to initiating fabrication and procurement of major components. This review occurs when the checklist of items, such as design and drawings are 100% complete; all review recommendations are addressed; safety, quality and procurement plans are completed; verification and acceptance test plans are complete; and installation and commissioning plans are in place.
- Approval to construct each major component rests with the Project Manager.

Findings: Project Management Systems (cont.)

- The Project has completed two dozen independent technical peer reviews for the Mu2e project systems and components. Review Team recommendations are then tracked through closure. Of the 157 recommendations from the Director's CD-3C Review and the Final Design Reviews, and some of these are recent, 54 recommendations remain open (ongoing resolution activities continue).
- The Mu2e Project Manager conducts monthly Project Management Group meetings where schedule, priorities, and staffing conflicts between the Mu2e project and the rest of the Laboratory are identified and resolved. Issues that cannot be resolved within the PMG can be elevated to the POG if necessary.
- An EVMS System is in place and periodic reporting occurs.
- A Change Control process, including a formal Change Control Board is in place. A specific procedure has been developed and is being implemented

Findings: Project Management Systems (cont.)

- Mu2e has a risk management process in place with a formal risk register. The Project is actively managing 80 specific risks; 70 of those are considered threats. Forty-two risks have been retired, while 11 new risks have been identified since CD-2. Both high and moderate risks are required to have individual risk forms that include mitigations. Mu2e reported that they performed a Monte Carlo PRA which predicts the Project will be completed within cost and schedule.
- Mu2e estimated that the available contingency is adequate to complete the project (consistent with the risk analysis).
- A Transition Plan, associated with the conventional facility construction, is well underway. This Plan focuses on an orderly transition, starting at beneficial occupancy, to experienced installation teams in the Fermilab operations group.

Findings: Project Management Systems (cont.)

- A Systems Integration process has been developed and is being implemented. Systems Integration includes requirements, interface control documents and design controls. The Systems Integration Team ensures that peer reviews and construction reviews are scheduled and conducted as well as commissioning and operations functions are planned and performed as defined. Integration Team members are on the Risk Management Board.

Findings: Project Documentation

- The Project provided all CD-3 prerequisite documents (Project Management, Safety, Technical Reviews, Risk Management Plan, etc.) to the Committee prior to the review.
- The Project also provided additional overarching project documents such as the Final Design Plan, Design Completion Definition; Key Assumptions, Design Reviews, Interface Documents, etc.
- A Transition to Operations Plan has been prepared for conventional facilities.
- Project responses to all DOE Review Committee recommendations from all prior DOE reviews (and Director's Reviews) are documented and provided to the Committee prior to the CD-3c review.

Comments:

- Mu2e is currently the largest baselined project at Fermilab and Laboratory leadership is visibly supportive of achieving project success.
- The Mu2e Project is well organized and sufficiently staffed by a highly competent and experienced management team. The nine Level-2 CAMs and their deputies are highly experienced, knowledgeable, and accountable for milestones, cost and schedule performance, critical paths, and multi-year staffing plans by discipline.
- The Laboratory leadership decision to increase and recruit highly competent procurement staff is commendable.
- The new QA manager is extremely experienced and has earned the respect of the entire project team. The addition of a skilled ES&H lead is noteworthy.

Comments (cont.)

- The availability of specialized engineers and, in the future, technologists needed for installation and commissioning, continue to be a concern. Staffing plans need to be negotiated as early as possible, then implementation tracked and trended to assure that quality engineers and technologists are deployed as needed by the project. Succession planning is to be part of this effort.
- The Acquisition Oversight Committee (AOC) can be an important asset, but appears to be under-utilized. The Project should examine the use of this Committee to determine its most effective use.
- The Review Committee was concerned and disappointed about the solenoid vendor's change in location for the solenoid production and the potential for an overall adverse impact to the project cost and schedule.
- Suitable project management systems are in place and are being implemented to successfully manage the project.

Comments (cont.)

- The Mu2e Project has a system to record review recommendations and track them through closure. The Responses to Recommendations documentation was very thorough and well developed. A number of noticeable changes (addition of ES&H staff, QA staff, design reviews, etc.) have been made consistent with the recommendations. While some actions remain open, acceptable plans are in place and these actions will be closed consistent with the finalization of the design work and/or Construction Readiness Review.
- While not all design activities are planned for completion as part of CD-3c, the issues associated with design completion are not significant and their associated risks are bounded. Mu2e constructability reviews, which are scheduled to be completed prior to construction/fabrication, will ensure the design activities are completed.

Comments (cont.)

- The Project needs to exercise care in ensuring that the procurement schedules are in sync with the EVMS. In an incrementally funded fixed price subcontract, it is important that amount funded be synced with the milestone payment schedule.
- The Project should initiate development of a preliminary, project-wide transition to operations plan that lays out the overall transition from a project to an operating facility. This preliminary plan should describe the overall strategy, and rough estimates of staffing and operating costs. The plan should be updated at least annually or when significant new information becomes available.
- Due to the large number of Project participants, the continued development of the project integration function is expected to provide dividends for the orderly implementation of the project.
- Muon Campus activities including General Plant Projects and Accelerator Improvement Projects are progressing well, reducing overall risk to the Project.

Recommendations

- By the end of July 2016, the Mu2e Project should develop a list of scope/performance items that could be funded if the contingency funds are not allocated by the end of the project.
- By the end of June 2016 include a standing POG agenda item topic on engineering staffing needs, status, and commitments to assure Mu2e project baseline schedule is maintained with minimum risk.
- Proceed with CD-3c.